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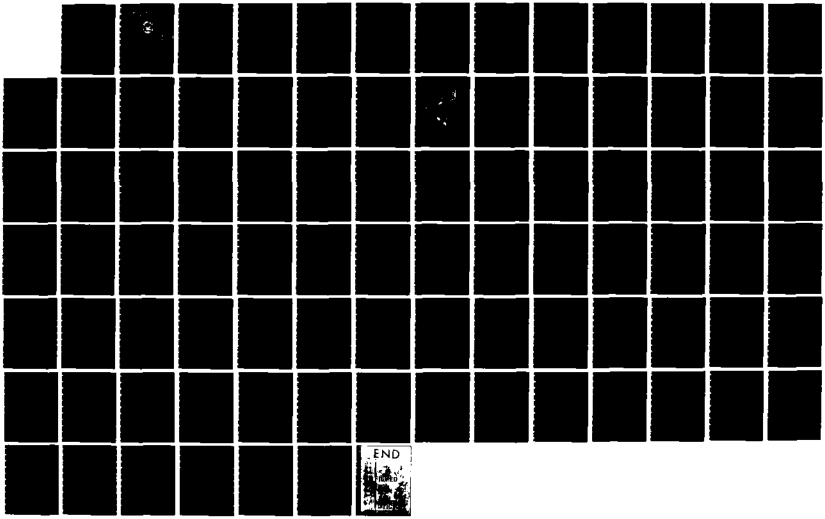

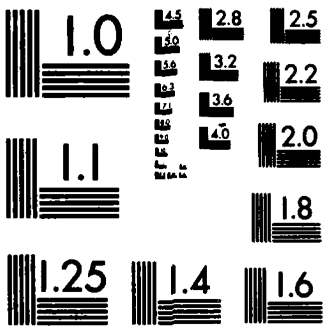

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THESIS

AN APPLICATION OF THE NAVSTAR GLOBAL POSITIONING SYSTEM IN NAVIGATION TRACK RECONSTRUCTION FOR NAVAL EXERCISES

by

Don Waymon Driskill

September 1983

Thesis Advisor: R. H. Shudde

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An Application of the Navstar Global Positioning System in Navigation Track Reconstruction for Naval Exercises

by

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Submitted in partial fulfillment of the requirements for the degree of

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I. INTRODUCTION

A. OBJECTIVE

As weapons and weapon's delivery platforms get faster, longer ranged, and more expensive to build, operate and maintain, the military must keep pace with the navigation accuracy requirements to maximize the effectiveness of these systems. Navstar GPS is being developed with this idea in mind. Also, as these systems are being produced, we must measure their operational capabilities and the tactics with which they are being used. One way that we measure these, in the Navy, is with at-sea exercises. The objective of this paper is to look at a somewhat different application of Navstar than just the simple integration into some type of vehicle. The purpose of this investigation is to determine the potential role of the Navstar Global Positioning System in exercise reconstruction for the Navy and what the impact of such a system could be in performing that mission. This thesis will examine a way that this information could be incorporated into the current reconstruction system. No attempt will be made to advocate this as either the only way or even the best possible way to use this new source of highly accurate navigation data. By incorporating this information into the system as it presently exists, both cost and development time could be saved and as will be

discussed later, a significant improvement should be seen in the navigation track reconstruction effort.

B. NAVAL EXERCISE RECONSTRUCTION

The reconstruction and analysis of Naval exercises provide the information needed by Fleet Commanders to evaluate operational capabilities and assess tactics of our seaborne forces. During peacetime, these at-sea exercises provide the closest approximation to a realistic wartime environment. At the same time, due to the tremendous expense involved in such full scale operations, maximum utilization of all data collected is an absolute necessity. While any given exercise is in progress, any one participant has only a partial picture of what is taking place. For instance, individual exercise participants do not know when or if an opposing unit was nearby but undetected. It is not until records of all exercise units are assembled after reconstruction that the entire picture can be deduced. Reconstruction is the process of resolving the uncertainties that existed during the exercise. It is the piecing together of these unknowns with the known information from particular exercise participants that ultimately produces a clear record of what happened. This includes, at times, the accidental destruction (exercise only) of friendly or neutral forces due to navigation inaccuracies, especially as ranges and speeds of potential targets increase and subsequent reaction times decrease.

Exercises can be exhaustively reconstructed and analyzed given the accessibility of position and event data from exercise participants. There is a much lesser capability to reconstruct and analyze other at-sea operations when information from non-cooperating units is not available [Ref. 1]. This paper will focus on exercise position data (as opposed to event data) for use in navigation track reconstruction.

C. NAVIGATION REQUIREMENTS

With regard to Naval exercises, which in turn are used to evaluate Fleet operational capabilities and readiness, specific navigation requirements are necessary to perform and assess all assigned mission areas. Navigation has an important affect on almost all Navy missions whether it be mine sweeping, weapons delivery, rendezvous of ships, aircraft tracking control, or simply crossing areas of the ocean (exercise areas). This navigation, the process of directing movement from one point to another, is frequently accomplished by determining a position, by a knowledge of direction, speed, and time, from which arrival at some other position can be determined. A number of available systems are presently in use to attempt to fulfill these requirements and a new system, the Navstar Global Positioning System will be evaluated in this thesis.

Most Naval tasks can be effectively accomplished by a system yielding position fixing accuracies of one to two nautical miles, providing the capability is continuous and

available in all environmental conditions. This accuracy is adequate for forces enroute to an objective area or essentially in port to port or long range point to point operations. Attack aircraft carrier striking forces, Anti-Submarine Warfare (ASW) forces, amphibious forces, replenishment forces, mine warfare forces, long range aircraft, and patrol forces have requirements for this capability in order to arrive at objective areas or to afford the widest flexibility in the deployment and utilization of forces on a world-wide (or exercise-wide) basis.

Some specific missions of Naval forces, most of which are evaluated to some degree by at-sea exercises, require more accurate position determination capabilities.

A few examples are as follows:

a. Fleet Ballistic Missile Submarine forces in order to attain design weapons effectiveness.

b. Attack Carrier striking forces in their objective area.

c. All long range ASUW (Anti-Surface Warfare) forces employing newer cruise missiles such as Harpoon or Tomahawk for over-the-horizon targeting.

d. Cruise Missile strike forces (various platforms) for precision delivery against land based targets.

e. Amphibious forces, landing forces, and shore fire support forces for the conduct and support of across the beach operations in objective areas. This includes

accurate positioning for ground-air operations, supporting weapons, and location and control of small boats (landing craft).

f. ASW forces in order to resolve ambiguities of contacts and enhance overall performance.

g. Mine Warfare forces while laying and sweeping mine fields.

h. Air operations on airways and in terminal areas (carrier or airfield) for safety of flight and for instrument approaches and departures.

In consideration of navigation accuracies required by some types and compositions of forces, relative accuracy is essential in other coordinated applications, especially in close quarters. The precise relationships between forces may be of a greater importance to the overall mission success than the precise absolute position.

The ultimate goal in navigation for the Navy, and for any similar user, is a completely self-contained system which provides the accuracies required of all its missions on a continuous world-wide coverage basis. However, until such a system is developed, the following navigation system characteristics are the goal. The following characteristics are considered by the Navy to be essential:

a. World-wide coverage.

b. Accuracy compatible with mission user.

c. All-weather.

d. Day and night usage.

e. Effective real time response.

f. Non-saturable.

g. Free of operationally significant ambiguities.

h. No electronic radiation by user (totally passive).

i. Determination of position upon activation of user equipment.

j. Size, weight, tactical portability and durability compatible with user application.

k. Virtually self-contained.

l. Common interface for combined operations.

The following characteristics are considered to be desirable for navigation systems and in some mission areas may be essential:

a. No foreign base rights required.

b. Easy to maintain and operate with high reliability.

c. Not line of sight limited.

d. Free of frequency allocation problems.

e. Denies enemy use.

f. No environmental propagation limitations.

g. Jam/spoof/meaconing proof (not subject to Electronic Countermeasures).

h. Invulnerable to sabotage or destruction.

i. Optimum cost effectiveness.

j. Optimum commonality and comparability with other existing or planned military and civilian systems.

k. Usable by submarines without exposure.

l. Places no altitude or maneuvering restrictions on aircraft [Ref. 2].

Many systems are presently in use that possess some of these navigation/position locating characteristics including celestial, Loran-A, Loran-C, Omega, Navy Satellite Navigation System and others. One new system that promises to possess many, if not all, of these attributes is Navstar GPS.

II. NAVSTAR GLOBAL POSITIONING SYSTEM

A. DESCRIPTION

Navstar Global Positioning System (GPS) is a space-based satellite navigation system designed by the Department of Defense (joint service project) to provide highly accurate three-dimensional position, velocity and time information to the user continuously, world-wide, and in all types of weather. It is currently in the Full-Scale Engineering phase of the acquisition cycle with initial two-dimensional operational capability expected by 1985 (nine satellites). Full three-dimensional capability is planned for 1987 when 18 satellites are scheduled to be in place. Full operational capability will provide users with position location information accurate to less than 16 meters (m) Spherical Probable Error (SEP--50 percent of the positions will fall within a sphere of this radius), velocity accuracy of 0.1 meters/second (m/s), and world-wide time transfer accuracy within 55 nanoseconds (ns) (55×10^{-9} seconds) to users anywhere within 500 miles of the Earth's surface [Ref. 3]. The GPS consists of three major segments: space segment, control segment, and user segment [Ref. 4].

The Navstar space segment was originally designed for a 24 satellite constellation as "celestial" reference points, but due to cost considerations was reduced to 18 satellites

in 1979. These satellites are to be placed in six, nearly circular, 10,898 mile orbits of 3 satellites each. This will produce 6 planes of satellites, 120 degrees apart (in each plane), each having a 12 hour period. A number of other 18 satellites constellations have been proposed since the reduction from 24 spacecraft with differing but important attributes, such that the final constellation configuration could be different when it is finally installed [Ref. 5]. The currently proposed deployment will provide adequate coverage (99.5%) for continuous and world-wide three-dimensional positioning, navigation, and velocity determination [Ref. 6]. This space-based radio navigation system's satellites will transmit accurately timed L-band frequencies: L1 (1575.42 Mhz) and L2 (1227.60 Mhz), each signal containing a precision (P) code and a coarse/acquisition (C/A) code. Each satellite transmits a navigation message that contains its precise ephemeris, clock correction data, and an "almanac" of orbital parameters and clock correction estimates for all other system satellites. The military plans to have the capability to deny the precise position information to other than authorized users in time of war. This is to prevent precise targeting capability by unfriendly users of our own Navstar system [Ref. 7].

The control segment consists of four widely separated ground-based monitor stations, presently located in Guam, Alaska, Hawaii, and California (all U.S. or U.S. controlled

territory) and a Master Control station currently at Vandenberg Air Force Base, California. The monitor stations passively track the satellites as they come into view. The monitor stations then transmit this tracking information to the Master Control station which, in turn, generates a navigation message which it uploads to each satellite on a daily basis. This information will be re-transmitted to the user by the satellite. This updated information is primarily aimed at keeping ephemeris (orbital parameters) within very precise bounds.

The Navstar user segment consists of user equipment (UE) containing a receiver and a navigation processor. The user set receives signals from at least four GPS satellites to continuously solve the user's three-dimensional position, velocity, and time. The UE acquires satellites by either normal hand-over mode (acquires C/A code first, then P code) or the direct mode (acquires the P code). Measurement, by the UE, of the relative delay between the two L-band frequencies allows computation of the ionospheric delay. The position solution is computed in an earth-centered, earth-fixed (ECEF) coordinate system: World Geodetic Survey 1972 (WGS-72) coordinates; and can be instantly converted to any of a large number of other reference systems that may be required by the user (this includes military grid reference system). The Phase I user equipments were of four types depending on application: X-set, Y-set, Z-set, and manpack (Manpack/Vehicle

User Equipment). The X-set is a high dynamic vehicle, four channel, dual frequency system that acquires all four channels simultaneously. This provides the user (vehicles such as high speed aircraft or missiles) a real-time instantaneous position. The Y-set is a single channel, dual frequency system that obtains information serially (sequential fashion). Position update is a function of the time it takes to cycle through the channels. It has an application in lesser dynamic vehicles (ships, tanks, etc.). The Z-set is a single channel, single frequency set that is also sequential in operation. This is considered to be the commercial fore-runner for GPS and is less accurate than the previously described units. The manpack is similar in operation to the Y-set, but due to size and weight restrictions is less accurate. It is designed for use by essentially immobile or very low dynamic applications (ground combat troops, artillery spotters, etc.) [Ref. 8]. In high dynamic applications the UE may be tied to an Inertial Measurement Unit (IMU) to maintain navigation accuracy during high acceleration maneuvers [Ref. 9].

B. SYSTEM OPERATION

The Navstar GPS system operates on the principle that the user determines his (pseudo) range (and range rate) from a number of GPS satellites (with precisely known ephemerides; orbital parameters) by accurately measuring the transit time of the navigation signal from the satellites to himself and

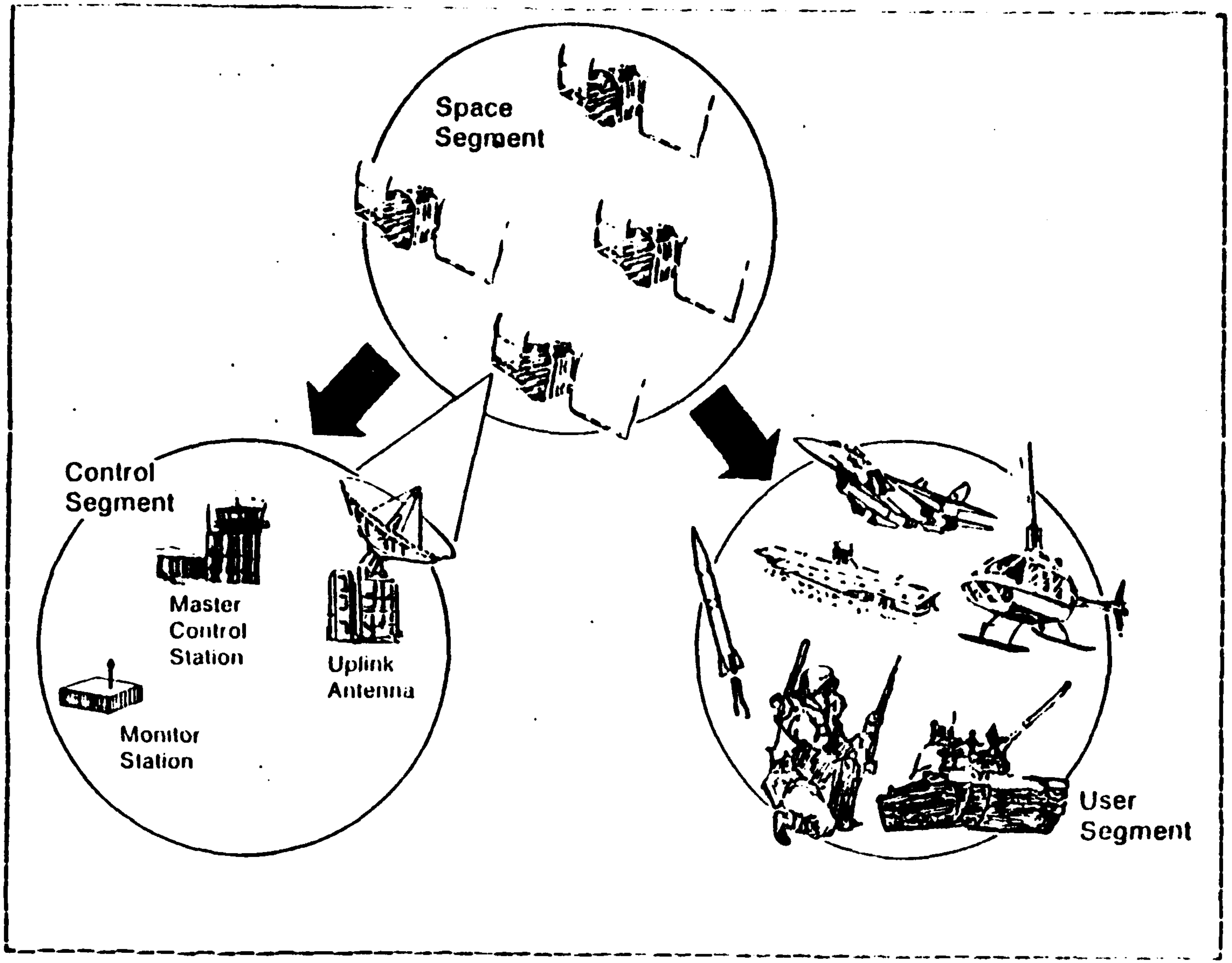


Figure 2.1. The Three Segments of Navstar GPS [Ref. 10]

multiplying that time by the velocity of light to obtain the distance traveled by that signal. Since the user's clock is not directly synchronized to the satellite clocks, this range measurement is in error by the amount of time offset, between the user and each satellite clock, and is therefore called a pseudo-range vice range [Ref. 11]. A three-dimensional navigation fix (position location) by a GPS navigator requires four GPS satellites since the navigation solution requires the computation of four unknown parameters: three position parameters (X,Y,Z earth-centered, earth-fixed (ECEF) coordinates; or latitude, longitude, and altitude geodetic coordinates) plus a time bias (Δt) between GPS time and the user clock.

These measurements of pseudo-range obtainable from the navigation message are given by:

$$R_i = RT_i + C(\Delta t_u - \Delta t_{si}) + C\Delta t_{iono}$$

where:

i = 1,4 satellites

C = the speed of light

Δt_u = time offset between user clock and GPS time

Δt_{si} = time offset between satellite clock and GPS time

Δt_{iono} = time delayed due to ionospheric and atmospheric effects

Δt_{iono} = Δt_{Ai} (Figure 2.1)

RT_i = true range from user to the i^{th} satellite

RT_i = $\bar{R}_i$ (Figure 2.1)

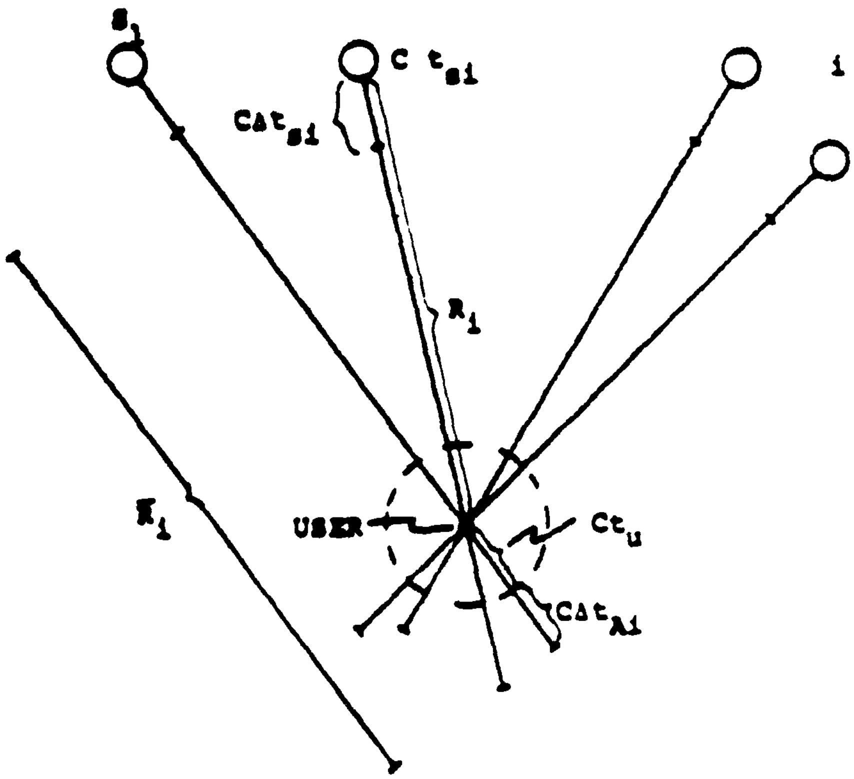
$$= \sqrt{(X_i - X)^2 + (Y_i - Y)^2 + (Z_i - Z)^2}$$

where:

X, Y, Z = user position in ECEF coordinates

X_i, Y_i, Z_i = i^{th} satellite position in ECEF coordinates

Satellite ephemerides will be periodically recalculated by the ground-based control segment of Navstar and uploaded to the satellites and provided to the user in the satellite navigation message. The user GPS receiver will be able to calculate the satellite's position (X_i, Y_i, Z_i) from these ephemerides. By using both the L_1 and L_2 frequencies, the time delay through the atmosphere, Δt_{iono}, can be calculated. The satellite will also provide the time offset between satellite and GPS system time, Δt_{si}. Thus the remaining unknowns that can be calculated by the four resulting independent linear equations are the user X,Y,Z coordinates (easily converted to latitude, longitude, and altitude) and Δt_u, the offset between user clock and GPS system time (actual time). As can be seen from above, if the user did maintain a clock synchronized with GPS time only three satellites would be required to obtain a three-dimensional GPS navigation fix [Ref. 12]. See Figure 2.2 [Ref. 13].



i = Space Vehicle

R_i = True Range

$\bar{R}_i$ = Pseudo Range

C = speed of light

$C\Delta t_{si}$ = i th satellite clock offset from GPS time

$C\Delta t_u$ = user clock offset

$C\Delta t_{Ai}$ = propagation delays and other errors

Figure 2.2 Pseudo-range Determination.

C. HISTORICAL BACKGROUND

The Navy began its first research on navigation by satellites in the late 1950s. Actually the Navy was navigating by "celestial bodies" with known locations for quite a number of years before that. In satellite navigation, the "celestial bodies" are just replaced by artificial satellites that can be tracked easily, such that their position is known with very little error. The initial satellite experiments were conducted by the Naval Research Laboratory (NRL) with research and development assistance by the Applied Physics Laboratory (APL) at Johns Hopkins University. It originated within the Navy as Project Transit and was developed to fulfill a requirement established by the Chief of Naval Operations to "Develop a Satellite System to provide accurate all-weather, world-wide navigation for naval surface ships, aircraft, and submarines" [Ref. 14]. The first demonstration satellite was launched, by the Navy, in April 1960. This was the first satellite of the Transit navigation system built and developed by NRL and APL. Transit became operational in 1963. It was first released for public use in 1969. Transit, or the Navy Navigation Satellite System (NNSS) as it is also called, is still in use today as one of the principle navigation systems by both the military and civilian communities. It has ably demonstrated the capability to provide position location information with nominal accuracies of one to two nautical miles (there have been several improvements since

the system was introduced). Although NNSS (nicknamed NAVSAT) is a good satellite navigation system, it does have some drawbacks. This system does not provide 24 hour world-wide continuous coverage nor can it be used on high dynamic platforms such as aircraft. In fact, depending on the location of the user there can be over an hour and a half between fixes in perfectly performing equipment, and then it still takes several minutes to calculate the location once the satellite data has been obtained. A better system was needed by the military to overcome these difficulties and to provide greater location accuracy [Ref. 15].

To make improvements in satellite navigation, NRL continued research and development in this field, and in May 1967, the TIMATION I satellite was launched. It demonstrated that lines of position could be determined from ranging satellites. It also showed that fixes from a single satellite could be obtained using both ranging and doppler plus time synchronization techniques. After further experimentation, NRL launched the TIMATION (TIMe navigATION) II spacecraft in September 1969.

In 1973, the Secretary of Defense directed the merger of the Navy's Timation project and the Air Force's 621B (satellite navigation) program. This produced the birth of the Navstar Global Positioning System. The final satellite in the TIMATION series was launched in July 1974. This spacecraft was subsequently renamed Navigation Technology Satellite

One (NTS-1) and became the first of a series of satellites launched by NRL to provide technical support for the GPS Joint Service Project Office. Numerous changes were made to improve NTS-1/TIMATION III, but the most significant was the addition of two rubidium (atomic) clocks for precise time measurement (and time transfer).

Finally, in 1977, NTS-2 was launched as the first satellite completely designed and built under the sponsorship of the Navstar GPS program. It was placed in a semisynchronous orbit at an altitude of 10,898 miles because that was the altitude selected for the operational GPS "birds". Instead of rubidium clocks, NTS-2 carried two cesium clocks. It also carried the same navigation subsystem designed for the operational spacecraft. During this same time period, but beginning in 1974, Rockwell International Inc., built six Navigational Development Satellites (NDS) [Ref. 16]. Five NDS and one NTS satellites were the spacecraft that started the Test and Evaluation phases of the Navstar project. Despite some atomic clock reliability problems, at least four satellites have been available for all important tests. During the 1983-1987 timeframe, the operational constellation of GPS satellites is scheduled for launch, and a shift to Space Shuttle deployment is planned.

D. ACQUISITION CYCLE

The Defense Systems Acquisitions Review Council (DSARC) which was held in December 1973, approved the basic Navstar

GPS concept and gave approval for the first of three phases of the acquisition cycle to commence. This first phase, the Concept Validation phase, was successfully completed in June 1979. The objective of Phase I was to evaluate the performance of two of the three Navstar segments: the user segment and the control segment. Six satellites were originally launched prior to Phase I and then, along with signals provided by the Inverted Range at the Yuma Proving Grounds in Arizona, were used to support this first phase. This was the start of Development Test and Evaluation (DT&E) of the traditional Test and Evaluation process.

Phase II, Full Scale Engineering Development, began in 1979 and is scheduled to end this year (1983). There were three primary objectives for Phase II. First, two contractors that were selected from the four leading competitors at the end of Phase I, commenced development of user equipment for host vehicles of this phase of testing. Secondly, spacecraft development continued in an effort to finalize the design for the operational constellation and preparations made for Space Shuttle satellite deployments. Finally, the operational ground control segment equipment and procedures continued development. The bulk of Phase II testing has been done at Yuma Proving Grounds, but some was conducted in Southern California near Camp Pendleton, in the San Clemente Island area, and in other waters near the Southern California coast. These areas were used since the test GPS

satellite constellation was configured such that maximum time and coverage could be obtained near these areas [Ref. 17].

The final phase of Navstar GPS is the Production and Full Scale Operational Deployment phase. The user equipments that best meet the users' needs in terms of performance and cost will be selected for production. This phase is scheduled for the end of 1983.

In summary, the three phased development and deployment of Navstar GPS is a step-by-step process in which the development and testing from the last phase is carried over into the production and procedures for the next phase. Throughout the process, system level testing will be done to select optimal equipments in terms of both performance and cost for the particular application of that unit [Ref. 18].

This chapter has provided a brief introduction to Navstar GPS. The next chapter will be an introduction and description of the Mini-Reconstruction System which can use Navstar data for navigation track reconstruction of Naval exercises.

III. EXERCISE RECONSTRUCTION USING THE MINI-RECONSTRUCTION SYSTEM

The development of small, relatively inexpensive, automatic data recorders and automatic data extraction devices for fleet units and the lack of availability of large mainframe computers to most fleet commands created a need to develop an automatic reconstruction system for use during at-sea fleet operations and exercises. The expense involved with at-sea exercises necessitates the extraction of as complete an evaluation of tactics, procedures, and weapons and personnel performance as possible each time such an operation is conducted. The complexities and speeds with which these events occur have produced a requirement for more sophisticated methods with which to process, reduce, and analyze the data generated. At the same time, there is a desire to produce the final result of an exercise as timely as possible for maximum benefit (while memories are still fresh) and still minimize the manpower and costs of such an endeavor. Such a system was developed to attempt to meet this requirement.

A. MINI-RECONSTRUCTION SYSTEM DESCRIPTION

The Mini-Reconstruction System (MRS), a component of the Tactical Information Management System (TIMS), was developed by the Naval Tactical Support Activity (NAVTACSUPACT or

NTSA), White Oak, Maryland to support Fleet Commanders in the evaluation process of at-sea exercises. MRS is a group of computer programs and associated procedures designed to provide a semi-automatic reconstruction and tactical analysis capability to fleet analysts for use by appropriate commands. The analyst operates interactively with the computer system and results are displayed on the video monitors. It is intended that the MRS be used for the purposes of reduction of automatically recorded data, reconstruction of tracks and events, and extraction of performance data from Anti-Submarine Warfare (ASW), Surface Warfare (SUW), Anti-Air Warfare (AAW), and submarine exercises. The use of MRS can reduce the burden of reconstruction on fleet assets and increase both the quality and timeliness of the data and results for use in "quick-look" (hot washup) critiques and debriefings. The MRS was designed and intended to be used in an at-sea or near real-time environment. In this context, "at-sea" is intended to be in time and in a location to carry out the MRS tasks prior to the hot washups or similar debriefings. At-sea could mean at staff headquarters, at a Naval air station, or aboard a major ship in the exercise. At present, there are seven Fleet sites that host a TIMS (and MRS) system. Originally, the MRS system was operated on an HP-9830A programmable calculator and associated peripheral equipments [Ref. 19], but is presently operated on an HP-1000 series mini-computer system.

MRS inputs are obtained from numerous sources including: seven-track computer tapes, tape cartridges generated by the companion Shipboard Automatic Recorder System (SARS) and Tactical Reconstruction Information Pod (TRIPOD) (aircraft only) systems, the TIMS system digitizer, and AN/SRN-19 NAVSAT tape cassettes. Data can also be entered directly through a TIMS keyboard. Outputs are generated on a system printer for numerical output and on the TIMS plotter for graphical presentation (navigation tracks).

The functional capabilities of the Mini-Reconstruction System include data editing and correction, interactive manipulation of graphics data, single-unit and multi-unit track rectification, contact and attack assessment, and generation of geographic plots, bearing/range plots, data summaries and graphs. See Figure 3.1 for the graphical representation of these capabilities [Ref. 20].

B. SYSTEM OPERATION

The MRS consists of four software subsystems: Track Rectification Subsystem (TRS); File Structure, Input, and Correlation Subsystem (FSICS); Performance Evaluation Subsystem (PES); and Extraction and Plot Subsystem (EPS). Each subsystem uses data inputs from recorded cassette tapes, seven-track computer tapes, keyboard, and all the other inputs listed above, plus the data entered in the MRS disk files.

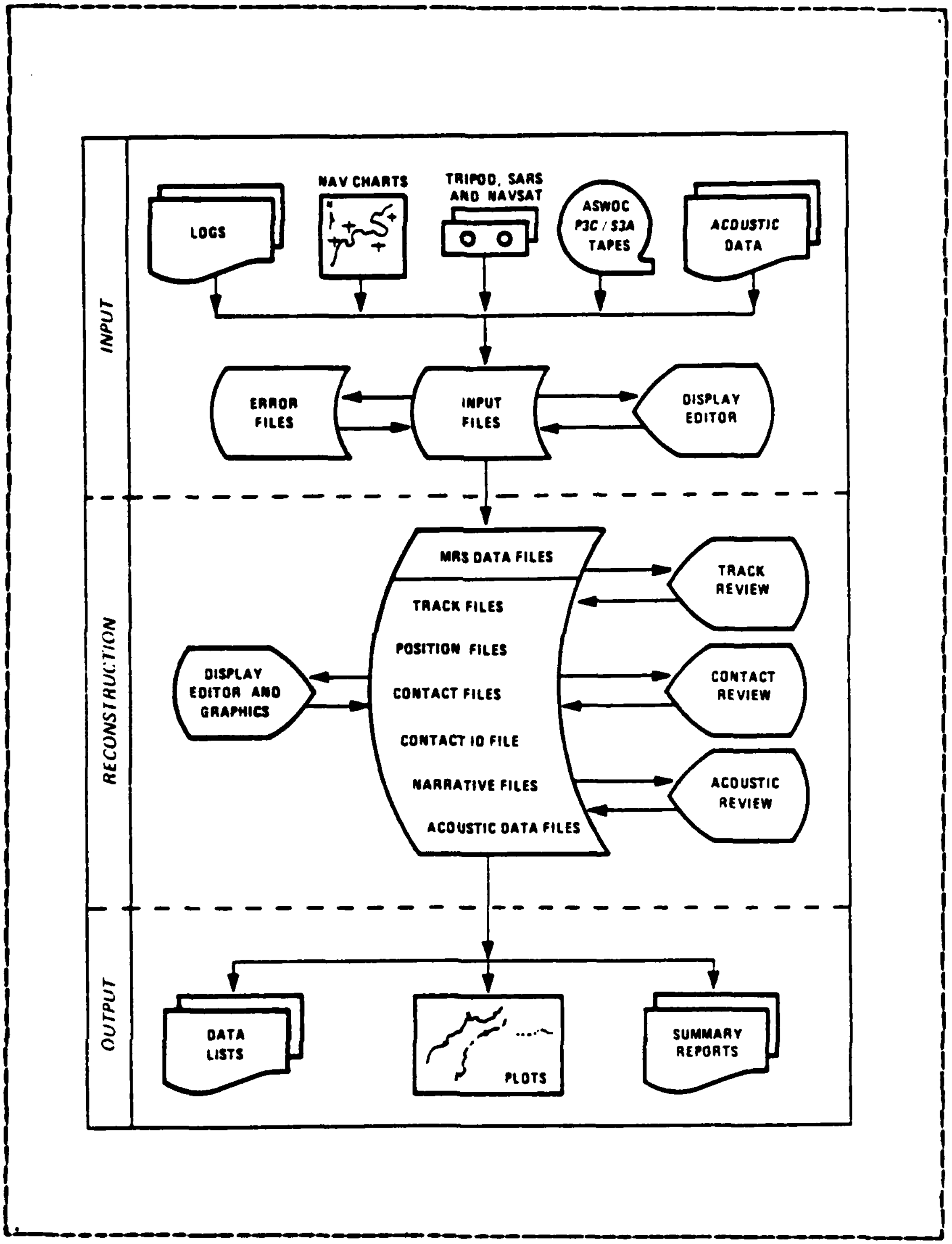


Figure 3.1 Mini-Reconstruction System Functional Diagram.

The Track Rectification Subsystem functions include processing input data to identify inconsistencies in position data, to create track files, and to rectify (create a smooth track from position and event input data) tracks. Track files are normally created by processing the input Dead-Reckoning (DR) data: course, speed, and time, or by connecting consecutive DR/fix positions to create tracks. Position information from position input sources are then edited for "bad" positions (done automatically by program and/or by analyst). The speed and course (DR) track files are then rectified (error corrected) to the position information, for the same unit, by a weighted least sqaures algorithm. This method gives heavier weights to the more accurate navigation systems. This will be described in more detail later. Basically, the track's shape is altered by moving position points or bending, stretching, or rotating track segments to obtain the "optimal" (most likely) track for that unit. The resulting single-unit tracks will have the same general shape as before rectification, but will fit more closely to the position inputs. The more accurate the navigation systems used, the closer the fit should be between the positions and the constructed DR track.

Once rectified tracks are produced for single exercise units, contact information is applied to these tracks to develop geographic positions for contact bearing and ranges which will be used for contact identification. This is called contact reconstruction.

Once the single-unit and contact reconstruction is completed, the Track Reconstruction Subsystem can again be used to rectify the composite locations of the multiple unit tracks. This composite will normally be done about a single unit with the highest probability of accuracy ("best" navigation system) or a force center unit such as the guide of the formation without regard for that unit's navigation accuracy. Relative placements of rectified single-unit tracks of selected exercise units is accomplished using the same weighted least squares fit technique for the unit tracks and the associated inter-unit contact reports. This will be described in more detail in Chapter V. This is known as Multi-unit Reconstruction. Once these tracks have been rectified to the user's (analyst's) satisfaction, they are inserted into the MRS file by the Track Insertion programs in the FSICS.

The File Structure, Input, and Correlation Subsystem performs a number of important functions. These are to structure the MRS files, to insert both tracks and lists into the MRS files, to merge track and contact data into the files, and to correlate data being inserted into the files with data already present there. This is the structure, administration, and construction subsystem of the MRS. Orange (enemy forces) track and contact data are normally entered directly into the MRS files using the merging programs and automatically correlated to Blue force (friendly force) data already in the files, by this subsystem.

The Performance Evaluation Subsystem (PES) has three primary functional program groups: Attack evaluation, Contact evaluation, and AAW performance evaluation. The purpose of this subsystem is to produce performance data to be input to files and produce performance reports for use by analysts in the analysis phase (after reconstruction). The attack evaluation portion takes attack input information, stores it, searches the files for correlation of all possible unit interactions within a given time period and location area (analyst selected radius) of the attack aim point. The output from this section is an attack correlation listing for analysis use. The contact evaluation section takes ASW contact information and stores it in contact files which can be interrogated for contact correlations. The AAW performance section inputs, primarily, detailed Orange AAW mission information and correlates this with Blue detection information to evaluate Orange air attacks.

The contact and attack correlation performed by the PES is basically accomplished by comparing "known" unit positions and evaluating opposing inter-unit contacts and subsequent attack geometry to determine if an attack occurred or if an opportunity was missed. MRS compares both Blue and Orange track files and contact files to determine these opportunities. The user can selectively display tracks of interest and retrieve contact and attack information to determine if interactions did or did not occur depending on

type of contact, its relative accuracy, and the analyst's evaluation of the track information. This same information can identify a missed contact if it was within sensor range (track geometry) and no contact information was generated and input to the files. In attack situations, the attacker's fire control solution can be compared to reconstructed track geometry to determine the probability of success of the attack.

The Extraction and Plot Subsection produces the products of reconstruction [Ref. 21]. These outputs are track plots, data lists, graphic displays, and graphs that are properly labeled outputs of reconstruction, but are not considered to be finished products of analysis. They are inputs to Fleet Exercise Analysis. Plot, extraction, and display programs give analysts the opportunity to retrieve *selected recon-struction* data from the MRS files.

There are three types of reconstruction products: plots, reports, and graphic displays. The MRS plot products are geographic track plots, bearing/range plots, and statistics vs. time plots. Reconstruction Reports are considered as hard copy or terminal displayed aids to the analyst, listing reconstructed information such as track histories, range and bearing summaries, etc. Graphic displays provide various levels of interactive reconstruction information in graphical format. This is the interface between exercise reconstruction and exercise analysis [Ref. 22].

C. HISTORICAL BACKGROUND

Beginning in the 1960's, technological advances provided less expensive, more compact, and better quality data recording and data processing equipment. Up to that time, reconstruction and exercise data collection was primarily a tedious, time-consuming process, involving hundreds of hours of manual labor. This started with data collection done primarily by manual log keeping: Engineer's Bell Sheet-speed data, Ship's Position Log-position location data, Ship's Deck Log-speed and course data, Contact Log-contact data, etc. Log keeping is still an important part of exercise data collection (OPNAV 3100 series logs), but is now mainly used as a secondary, or back-up, data collection method for navigation track reconstruction. The earlier years of exercise reconstruction consisted of navigation tracks constructed from time, course, and speed information (DR), fitted to a very few, relatively inaccurate, position fixes. This data was the information of primary interest collected by logs.

The first computer-aided exercise reconstruction efforts consisted of key-punched data from logs, processed on large main-frame computers at shore based commands. Around 1967, when programmable calculators became available to the fleet, there was an effort by sea commands to develop an at-sea reconstruction capability. Between 1967 and 1975, there was a determined effort to produce the software to meet the

fleet's requirements. By 1975, a large number of fleet exercises had been reconstructed by computer-aided methods. The early at-sea programs were developed primarily by COMCRUDESGRU EIGHT, Naval Air Development Center, Naval Research Laboratory, or NAVTACSUPACT (NTSA). COMCRUDESGRU EIGHT developed the first programs for use on the Hewlett Packard 9830A programmable calculator which was the first widely available fleet support hardware. Some of the data files used with the initial version of the Mini-Reconstruction System were developed by COMCRUDESGRU EIGHT. During this same time period, the methodology behind track reconstruction started to change also. When methodology changed, the programs had to change also. The reason for the change was the improvement in some of the newer navigation system accuracies and times between fixes. This produced more position location information, so less emphasis was placed on generating the DR, and more emphasis was placed on fitting the DR to the position data.

By 1975, these systems had been refined and expanded such that a significant amount of time and effort reduction had occurred in reconstruction. However, with all the increased research activity in this particular field, there was a need to have control of this software development and almost rampant growth to ensure uniformity, dissemination of new developments, and quality of both software and hardware support. NAVTACSUPACT (NTSA) developed a share library of

Fleet Reconstruction/Analysis Systems computer software programs to support fleet exercises and operations. It also developed procedures to maintain software administrative control, software support in the form of program changes and documentation, and support in the form of research and development of reconstruction programs. It also provided for distribution of this material, and information regarding this material, to appropriate activities [Ref. 23].

As described, NTSA consolidated the software activity. In addition, hardware in the form of digital data recorders, automatic paper tape punches and readers, Naval Tactical Data Systems (NTDS), and line printers were developed which aided the data collection effort. Programmable calculators and eventually smaller (less expensive) computers also became available.

NTSA eventually combined and refined the software to produce the present Tactical Information Management System of which the Mini-Reconstruction System is an important part. It now operates on the HP-1000 mini-computer suite and associated peripheral and support equipments at seven Fleet locations.

IV. METHODOLOGY

This section will describe the ways that Navstar GPS information can be collected and used for exercise reconstruction. Phase II GPS user equipments were designed to operate in some thirty different host vehicles and will be specifically integrated into the following vehicles during this Operational Test and Evaluation (OT&E) phase. These vehicles are: Tank (M60), Helicopter (UH60), Attack Aircraft (A6E), Fighter Aircraft (F16A), Maritime Aircraft (P3C), Bomber Aircraft (B52D), Aircraft Carrier (CV64), and Submarine (SSN). This demonstrates the widespread application possibilities for the Navy, since the Navy has vehicles in most of these categories. This section considers the interim period of Navstar use, prior to complete installation levels in fleet units, and its use in fleet exercise reconstruction.

A. DATA COLLECTION METHODS

1. Permanent GPS Installations

When Navstar GPS becomes operational, some Naval units will be fitted with Navstar user equipments as soon as possible. These units will provide a nucleus of ships, aircraft, and other vehicles with this highly accurate navigation capability. In an at-sea exercise, it would be a logical choice to select these units with the most accurate

navigation systems available, to perform initial single-unit rectification and reconstruct their navigation tracks. Contact evaluation/correlation with these units is the next logical step in this process. Finally, multi-unit rectification of navigation tracks could be accomplished.

Several ways to collect these navigation data from permanently installed user equipment (UE) are feasible. If the unit is a Naval Tactical Data System (NTDS) capable ship, station, P3C or S3A aircraft, data collection can be performed quite easily. Whether the Navstar UE is integrated directly into the NTDS system, so that navigation information is continuously input to that system, or manually entered periodically (periodicity as specified by the NTSA Fleet Exercise Data Collection Manual) from the Navstar receiver output, this information is readily available in a format directly usable by NTSA's Data Translation System (DTS) and subsequently by the Mini-Reconstruction System. These data can be collected by one NTDS unit participating in a Link-11 (computer-to-computer) radio communications link with other Link-11 units, and the data from all participating units extracted on the NTDS magnetic tape recorder of this one unit. Each unit could data-extract its own NTDS Link-11 information on magnetic tape. Any participating unit could collect Link-14 NTDS (broadcast to all units, especially important to non-NTDS units) data, usually in a paper tape format, which can also be used directly by the MRS (via DTS).

The installed UE could be designed with a cassette tape recorder capability. The recorder would not have to be installed at all times and could be obtained from NTSA in the same manner that "portable" exercise equipments are now obtained. This cassette data would be recorded in a format directly usable by the MRS.

NTSA sponsored the development and design of the Shipboard Automatic Recorder System (SARS) as a companion equipment to the MRS. SARS is a portable, automatic data collection system that is temporarily installed on ships during exercises and operations. SARS is self-contained and is installed and operated by NTSA personnel. It records data extracted from ship sensor and navigation systems, plus manually-keyed contact and event data. Navstar data could be input directly into SARS. Information recorded on SARS tape can be directly input into the MRS [Ref. 24].

Some of the newer ships, such as the Spruance class destroyers, have an integrated navigation system. This system inputs several different navigation systems into a Kalman filter that integrates the inputs into computed positions to produce a smooth navigation track. Presently, the primary input into this system is NAVSAT (satellite navigation system), with a hyperbolic radio navigation system such as OMEGA added. Additionally, the system compares the ship's speed and course (Electromagnetic Log and Gyrocompass) information for Dead-Reckoning (DR) inputs. The difficulty

with this system, as presently configured, is that the time between fixes for NAVSAT can be long (nominally 90 minutes, but could be much longer) [Ref. 25]. This problem could be solved by making Navstar GPS the primary input into the integrated navigation system. This information could then be collected either by using NTDS extraction or the SARS equipment as described above.

Finally, Navstar data could be collected manually by proper use of the Ship's Position Log. These positions would be input into the MRS by keyset entry. This particular collection method, due to its manual nature, would likely be reserved for secondary or back-up collection of exercise data.

2. Temporary GPS Installations

When exercise data are collected for ships, the navigation system that presently provides the most accurate data is NAVSAT. However, a number of ships don't have this higher accuracy satellite system. Therefore, in order to take advantage of this system for exercises, a portable NAVSAT system was developed and provided by Navy Tactical Support Activity (NTSA). It was introduced into the Fleet in the 1974-1975 time frame. This device was the AN/SRN-19 Navigation Satellite Receiver/Recorder. The SRN-19 consists of a self-contained receiver with a built-in cassette recorder, a printer, and an antenna assembly. It is installed in the chart room or on the ship's bridge for the duration

of an exercise. This system can provide own ship's position periodically on a hard copy printout and record it for reconstruction purposes on a cassette tape. These systems are requested from and installed by NTSA personnel [Ref. 26].

It is envisioned that just such a receiver/recorder system based on Navstar GPS would be a highly desirable addition to NTSA's portable exercise locker. Not only would this system provide better accuracy than NAVSAT, but the time between fixes, and coverage of the GPS would provide a considerable improvement over existing capabilities. Chapter V will address the specific details of this anticipated improvement. In fact, this portable system capability, based on the Manpack version of Navstar was successfully demonstrated during Rimpac '80 exercises [Ref. 27]. Additionally, palletized versions of both the X-set and the Y-set UE were used in a portable fashion for initial shipboard testing. Whether one of these systems would be selected to mate to a recorder and become the SRN-19 replacement (based on Navstar) is speculation, but such a system is very much needed to upgrade reconstruction capability, especially until GPS is a permanent fixture in most fleet units.

For submarine applications, the temporary unit should be based on the X-set type UE, since this multichannel unit can obtain simultaneous GPS satellite signals, and could produce a fix in a much shorter time than a single or sequential channel set. This would provide a much

shorter exposure time for a submarine at periscope depth to obtain this position fix and then return to a safer depth. In addition, a submarine would have a much shorter exposure time using Navstar than NAVSAT since the submarine NAVSAT antenna must be exposed while the fix is being computed (collecting doppler information, etc.), while the Navstar antenna must just be exposed long enough to pick up the "visible" Navstar satellite signals (seconds) and then submerge to perform the fix calculations. The basic difference between the surface and submarine units in addition to type of receiver required (sequential vs. simultaneous type), would be the location and, very likely, the type of antenna assembly mounted on the units. The submarine antenna, unless a new type of antenna is developed, would by necessity have to be mounted in similar fashion to the present NAVSAT antenna. This antenna would have to be designed for use at periscope depth, and would very likely be mounted in approximately the same location as the present satellite navigation antenna.

For aircraft applications, the Tactical Reconstruction Information Pod (TRIPOD) is presently in use. TRIPOD is a self-contained, pod-mounted automatic data collection system which is mounted on the aircraft weapons pylon. It interfaces with the aircraft only for power and for manual event data input. The pod has equipment to determine altitude, heading, speed, and position (Loran-C) and a cassette

recorder [Ref. 28]. Replacing the Loran-C equipment with Navstar GPS equipment would be sufficient to upgrade the TRIPOD to include this new capability.

An economical missile and target drone track reconstruction technique could be accomplished by fitting these vehicles with a Navstar antenna unit to receive Navstar satellite signals. The data could then be translated to S-band frequency signals, and re-transmitted to a ground station. At the ground station, the received signal could be processed and the normal pseudo-range and range-rate measurements of the missile or drone computed. In addition, the ground station obtains its own Navstar signals, which are used as a reference, in order to reduce any bias that may be common near that location and this bias is removed from the computed data. A Kalman filter then obtains the final positions and velocities of these vehicles. The reason that this technique is so attractive is that with missiles, and sometimes with drones, the vehicle is expendable and will make but one flight. This technique is highly accurate and is economical since a complete Navstar GPS user set is not lost with each flight. Additionally, this technique will provide both a tracking and a reconstruction capability for the system. This technique has already been implemented in the tracking of Trident I (C4) missiles (Satrack system), with the exception that Satrack is intended for post-flight processing of data, while the above proposed system is intended

for use in real-time [Ref. 29]. Also, in addition to the above described vehicles, any unit could be fitted with an antenna (GPS), S-band translator, and transmitter and as long as it was within radio range of a ground processing station (possibly a ship) to produce relatively inexpensive exercise track information for reconstruction. For most units, including exercise missiles and drones, the transmitter already exists (i.e., telemetry information requirements for missiles and drones) further reducing the costs of additional equipment.

The data collection techniques discussed above are not alternative methods for accomplishing the same mission, but rather different methods for accomplishing track reconstruction for Naval exercises depending on the widely varied application requirements. These methods can, for the most part, be accomplished using rather slight modifications to existing operational or prototype equipments. This is in keeping with the objectives of this paper to look at methods that are currently available to incorporate Navstar into exercise reconstruction. New and better alternative methods for data collection may be developed as Navstar begins its operational phase, but not without the probability of significant developmental costs and resources.

B. EXERCISE RANGES

With the exception of the missile tracking system, described above, none of the techniques discussed so far are

location dependent. Although Navstar GPS is quite accurate (nominally 15m SEP), there may be exercises where greater accuracy is desired. There are a number of tracking ranges (exercise ranges) at various fleet locations employing high accuracy tracking devices to measure an exercise unit's position including: lasers, optical trackers, high precision radars, sonar hydrophones, Mini-Ranger III, etc. Some of these trackers are very accurate (mean accuracy error < 2.0m), but are also very expensive. The introduction of Navstar has provided a new way to build a relatively inexpensive tracking range which has an application in exercise reconstruction. This technique is called Differential Navstar or Differential GPS. Differential GPS represents a cost-effective straightforward method to significantly improve the accuracy of GPS user sets. The focal point of the differential system is a GPS receiver (differential sensor) that operates from a geodetically surveyed antenna location. The "true" values of this receiver's antenna location are compared against the measured values of the same receiver's computed position. The differences between the two values become the differential corrections (bias error corrections). These corrections can then be transmitted to users in the area, in real-time, to apply to their navigation data to produce position fixes free of GPS-related biases. These differential terms tend to change slowly, so no sophisticated system is required to apply these corrections. Since the

common errors are generally the largest component of system error, this technique provides significant improvement in accuracy over the unaided system (on the order of 5 meters error), within the general area of the surveyed antenna [Ref. 30]. To set up a range for an exercise requires a surveyed antenna location, one GPS receiver/antenna unit, a processor to determine differential corrections (no sophisticated system is required), and a transmitter/receiver set. This is not only a cost-effective exercise range, but one that can be set up on very short notice. Collection of data would be accomplished as in Section A above.

C. REAL-TIME RECONSTRUCTION

The use of Navstar GPS coupled with the Mini-Reconstruction System (MRS) provides the potential for highly accurate real-time exercise reconstruction. As discussed previously, MRS is designed for "at-sea" (real-time) reconstruction. This could be a new revolution in the conduct of fleet exercises. In previous exercises, the results of encounters (attacks) were not usually known to Blue or Orange commanders until several hours or days after that event. These results were only speculative. Attacks, especially the over-the-horizon type attacks, were just a series of probabilistic draws (rolls of the die) conducted by an umpire, once a target was detected (hopefully identified) and attacked. Now, the tracks of opposing units can be reconstructed, fire-control

solutions inspected, and only the terminal phases of the attack determined probabilistically, to get a realistic attack determination in real-time. This would make the exercises more realistic, provide the commanders with better information on how a particular battle (exercise) was going, and make the umpires' jobs easier. Additionally, units would be forced to do more to localize and target opposing units, rather than to just detect, fire a weapon, and then hope for a probabilistic hit. This would greatly improve the training and evaluation of fleet units in at-sea exercises.

All the above information is normally obtained from the analysis of reconstructed fleet exercises now, but not with the accuracy of Navstar navigation data, not in real-time, and not normally without a great deal of effort. The final outcome of a fleet exercise may not be known for weeks or months without this immediate reconstruction from systems such as MRS.

V. NAVAL EXERCISE RECONSTRUCTION AND GPS IMPACT ON THIS PROCESS

A. SINGLE UNIT RECTIFICATION

When analysts perform single unit reconstruction (SUR), they are performing two basic processes. These processes are: (1) Consistency Analysis (CA) and (2) Single Unit Rectification (SU). Both require analyst input parameters prior to program execution. Those input parameters, processes, and impacts of selected sensor information will be included in the following sections.

1. Consistency Analysis (CA)

Consistency analysis is the process used to identify track shape errors or "bad" reported positions (posits) prior to the rectification process. This is done by comparing the generated dead-reckoned (DR) track with reported posits during the same time interval with a user selected tolerance factor selected. The basic process is vector addition with the vectors being speed and course vectors originating on the first posit, for a time interval of interest, plus a 360 degree vector representing the tolerance factor for subsequent posits. Depending on whether or not one or more of the successive posits fall within the tolerance vectors' reach, a posit can be considered to be "bad" or an inconsistency can exist. Inconsistencies are dealt with by generating error vectors that are vectors that

represent errors in DR track shape. "Bad" posits are flagged such that they can no longer be used by subsequent CA or single unit rectification until such flags are removed.

Selected tolerance factors can have a profound effect on this process. If posits and track data are considered to be fairly accurately collected and recorded, then a smaller tolerance factor may be selected, and if the converse is indicated, then larger tolerance factors should be used. If no prior information is known about the data, it may be that several tolerance factors may have to be tried to get satisfactory results. The use of the correct tolerance factor is therefore a function of the experience of the user (analyst) and any prior knowledge about the input data.

Consistency analysis (CA) output contains the track errors that have been identified. This output is used for the correction of the data input into single unit rectification (SU) process. CA output provides the time interval, track shape error vector, the posit to posit course/speed, and the average track course/speed. If "bad" posits are identified, the output provides the time and population type for the posit (it will not be used in subsequent SU). If inconsistencies are identified, the analyst should use the generated correction data to correct or delete erroneous track position info prior to the SU process.

Although CA is an important part of Single Unit Reconstruction it will not be focused upon in this paper.

It is primarily used to identify totally inconsistent data usually attributed to collection, recording, or contact correlation errors. System accuracy or performance errors should be accounted for by the rectification process which will be focused upon in this study.

2. Single Unit Rectification (SU)

The single track rectification algorithm was based on the classical statistical technique called the method of Maximum Likelihood. The basis for the use of this technique is the assumption that the nature of the errors or "differences" between tracks, positions, and inter-unit contacts are the result of imprecise measurements and small, slowly changing errors in the measurement systems (inaccuracy). Such errors include: compass errors, pit-log errors, set and drift, atmospheric refraction in radio navigation systems, time inaccuracies in satellite and celestial systems, calibration errors of electronic equipments, etc. The sources of these "differences" for any given moment of time are not known (although the general sources of error can be determined), therefore there can be no absolutely precise algorithm developed for track rectification. Even if these "differences" or errors could be known, the degree of dependencies between them can not be precisely determined, moment by moment. Since the nature of these errors is such that they can not be precisely and independently determined, and are considered to be constantly changing, the assumption is

that these errors are random variables. The Central Limit Theorem of statistics shows that combinations (sums and averages) of reasonably well-behaved random variables are approximately normally distributed. Therefore the assumption is that the solution required to accommodate the various combinations of variables (errors) contained in a track rectification can be reasonably approximated by an algorithm based on the normal distribution (in this case based on the method of Maximum Likelihood). The Likelihood of a sample $y_1, y_2, y_3, \ldots, y_n$ taken on the random variables $Y_1, Y_2, Y_3, \ldots, Y_n$ is defined as the joint density evaluated at $y_1, y_2, y_3, \ldots, y_n$. In the method of Maximum Likelihood, we choose as our parameter estimates, the values that maximize this joint density.

As previously described, since no rigorous computationally precise algorithm is possible, certain properties of a "good" solution are desirable. The developed algorithm of MRS has these properties of a "good" solution:

(1) All types and combinations of observations should be accommodated simultaneously (or in a way to achieve this same effect).

(2) Greater precision or reliability observations should have greater influence on a solution than lesser precision or reliability observations.

(3) No single datum can be assumed to be irrefutably exact, therefore the final solution is a compromise of all inputs into the algorithm (not even Navstar's

impressive performance to date can justify the use of only one single navigation source for safe navigation or for reconstruction).

(4) The adjustment of track nodes (segments of DR track where courses and/or speeds change) is affected more by closer observations than farther observations in time.

(5) Rectification should not introduce new nodes (should not generate new data points; only process the old ones).

(6) Final solutions consist of complex combinations of translation, bending, and stretching of track segments, not usually an easy accomplishment.

Due to the partial correlations of the aforementioned variables in the rectification process, it is quite difficult to estimate the precision of the final computed track on an absolute scale. However, it is possible to compute parameters that relate the relative precision and accuracy of computed tracks. These parameters output by the single unit rectification process can be used as weighted least squares relationships for later use.

In the Maximum Likelihood method, track bending, and stretching functions could be quite complex. However, these effects can be approximated by simpler translations that are not stochastic; that are time invariant and linear. Basically the track segments can be divided up into linear segments,

(vectors) over short time intervals, from which these transformations are obtained. Actual rates of change in the rectification parameters can be derived from the transformation computations in these intervals.

These time segments (parameter set spacing) or "time windows" on each side of a parameter set define the interval from which position and contact observations are included for computing that particular parameter set. That parameter set spacing must be long enough to include several observations to develop a rectification parameter set that has some meaning. Therefore, these "time windows" must be, and are selectable (user selectable) in the MRS system. These windows can be used to include different data sets with significantly different distributions of observations in time.

The SU algorithm of the MRS uses an exponential function to decrease the influence of an observation over increasing time separation from the parameter set time. This function is one way to represent a decay over time (probably the most classical way). Other ways would be to use a decreasing linear or power series over time as long as they were monotonic decreasing functions. However, the exponential function provides a substantial increase in the ease of both derivation and computation to accomplish this delay. Additionally, this computation efficiency provides a direct reduction in computer time and therefore cost.

Track rectification is accomplished by using a method known as weighted least squares to adjust the generated track node (point of interest where course and/or speed changes) to provide a "best fit" to those reported positions (posits) falling in a time period around the node. Each track node has a set of translation parameters that are generated from interpolating along the rectification parameter sets that are computed for fixed intervals throughout the track length. These translation parameters are used to correct for the small, slowly changing effects that account for the differences between a unit's true track and an accurately generated DR (computed as previously described by the method of Maximum Likelihood). The fixed interval, used to identify the places where parameter sets are computed, is called the parameter set spacing. This user input spacing can have a value between one and two thousand minutes. There is no correct value for this analyst selected spacing, but some general guidelines are: if the reported positions are believed to be highly accurate, then short time spacing should be selected to get a good fit and if the posits are believed to be of variable accuracy, then larger time spacing is desired to get more of the averaging effect.

3. Relative Position Weights

The relative weighting of reported positions, when performing track rectification, depends on several factors. These factors include: position quality, position type, and

the time difference between the reported position and the parameter set being computed. These are discussed in the following paragraphs.

U.S. Navy navigation procedures describe position qualities as: excellent, good, fair, poor, or "no fix". Whether the reported positions are entered manually or automatically a position quality is entered. In NAVSAT cases, position quality is computed, along with the position fix, and recorded, based on such factors as numbers of dopplers received, noise measurement value, and elevation of satellite. The same is true of Navstar, in that an estimate of fix quality, based on a value called the Geometric Dilution of Precision (GDOP), is also automatically computed and this recorded value can be converted to a position quality. The value of GDOP is in part a function of the geometric configuration of the satellites that are being used at the time by the GPS user equipment. Other position qualities may be estimated by the navigator of the unit whose track is being reconstructed. These position qualities are assigned a relative numerical value from one to four corresponding to poor to excellent qualities respectively.

Certain populations of position types (navigation system types) are considered more reliable and accurate than others. In order to determine the relative weighting between positions, a weighting factor is input to the rectification process. This weighting factor is a value between

zero and one hundred based on the position type being considered. Prior to execution of the single unit rectification process, the analyst selects the desired weighting factors in the MRS rectification matrix.

This weighting factor is based on the accuracy of the navigation system of each position type. Therefore, this weighting factor should just be inversely proportional to the error variance of this particular population (system) type. So, this weighting factor is w_i, where $w_i = 1/\sigma_i^2$, for each population type. This variance σ_i^2 could be estimated by $\hat{\sigma}_i^2$ which would be the historical variance information collected for each system type (sampled error variance). Therefore the weighting factors should be: $w_i = 1/\hat{\sigma}_i^2$. These values would probably have to be scaled such that all values would fall within the zero to one hundred interval, but relative weights would not change. The difficulty with such a scheme is that as the accuracy of navigation systems increase relative to each other, the value of w_i increases to infinity instead of one hundred. If the accuracy of the "best" system (in nautical miles) was 0.1 for a one standard deviation error, then the corresponding $w_i = 100$, providing the upper limit. For example, if Navstar GPS accuracy (based on phase I data) was 0.1 nm for a one standard deviation (SD) error (this is a very conservative estimate as this value was 11.1 meters (m) for 50% probability error and 15.0m for a one standard deviation error, based on a bivariate normal

distribution-circular error) [Ref. 31], then $w_{gps} = 1/(0.1^2) =$ 100 (highest weight possible). Other navigation system w's would be calculated in the same manner. However, if a more accurate error estimate is used for the "best" navigation system and all other systems scaled proportionally other problems could arise. For example, if a one SD error of .008 nm was used (closer to the actual observed value), the subsequent weight would be approximately 15625, therefore requiring a scaling factor of 1/156.25, to have all weighting factors within the allowable range of zero to one hundred. Then, this scheme would have the effect of giving the most accurate system all the influence (weight) and the lesser accurate systems almost no influence. Therefore, if the accuracy of at least one system, is very much more accurate than all the other systems, the scaling factor may have to be some function of accuracy error, such that the lesser accurate systems would not be totally disregarded. A more appropriate weighting factor w_i, could be $w_i = 1/\hat{\sigma}_i$; that is, inversely proportional to the standard deviation of the sampled error (this is just variance transformed by a simple power transformation, in this case the power is 0.5) to get reasonable weighting factors in the proper range (or close enough to use a very minor multiplicative scaling factor) for all types of systems. The current default values in the MRS system for weighting factors are: DR--10.0, Estimated position--20.0, Loran-A--40.0, Loran-C--40.0, NAVSAT--80.0, SINS--20.0,

and other types--20.0. Based on relative accuracy, GPS would have to have the maximum value of 100.0.

When time separation between reported positions and a parameter set time is short, these positions have a greater effect or influence than positions farther in time from the parameter set. This can be accomplished by applying a computed coefficient to the basic weight of each reported position. This coefficient is computed by applying an exponential function to the time differential between the position time and the parameter set time as discussed previously. The weighting used in parameter set calculation for each position report will be:

$$W_j = w_j \times \exp - (|t_p - t_j|/S_p)$$

where:

w_j = basic weight for the j^{th} position report based on the navigation system used and position quality;

t_p = time of the parameter set;

t_j = time of the posit report;

S_p = parameter set spacing.

The total relative weight that each position will have in computing the parameter set at time t_p is:

$$W_1 = w_1 \times \exp -(|t_p - t_1|/S_p)$$

$$\vdots$$

$$W_n = w_n \times \exp -(|t_p - t_n|/S_p)$$

Once the parameter sets from rectification are generated, the position of each track node in the unit's track file will be corrected. This correction will be performed by adjusting this position in accordance with the translation parameter sets described previously. Finally, a printed output will be developed, summarizing the translation criteria developed for each parameter set [Ref. 32].

4. Mathematical Basis for the Single Unit Rectification Process

The following mathematical model is used for the MRS Single Unit Rectification Process:

Definitions:

t_i = time of the i^{th} position;

(x_i, y_i) = values of the computed track at time t_i;

(X_i, Y_i) = reported position at time t_i;

(xx_{ji}, yy_{ji}) = rectified position at time t_i, for j^{th} time period.

Assumed parameter relationships based on the Maximum Likelihood method:

$$(1) \quad \begin{cases} xx_{ji} = x_i + l_j + (u_j t_i) \\ yy_{ji} = y_i + L_j + (v_j t_i) \end{cases}$$

(rectified posit = computed DR track + parameter est.)

where:

l_j = translation in the longitude direction;

L_j = translation in the latitude direction;

u_j = time varying translation in the longitude direction (set and drift);

v_j = time varying translation in the latitude direction (set and drift)

are the parameter estimates to be maximized in the method of Maximum Likelihood, to minimize the variance of the estimates for the rectified positions. We must determine l_j, L_j, u_j, v_j so as to minimize the following quadratic function (i.e., minimize the sums of squares of the distances between the rectified positions and reported positions--weighted least squares portion of the algorithm):

$$(2) \qquad W_j = \sum_{i \epsilon I(j)} (1/\sigma_i^2)(xx_{ji}-X_i)^2 + (yy_{ji}-Y_i)^2)$$

where the quantities x_i, y_i, X_i, Y_i, σ_i are given.

Defining,

$$(3) \qquad dx_i = X_i - x_i, \quad dy_i = Y_i - y_i$$

and substituting from (1) into (2), we obtain

$$(4) \quad W_j = \sum_{i \epsilon I(j)} (1/\sigma_i^2)((-dx_i+l_j+u_jt_i)^2+(-dy_i+L_j+v_jt_i)^2)$$

The set I(j) in the preceding equations is the subset of the integers i which occur in the j^{th} time period.

Defining,

$$(5) \qquad w_i = 1/\sigma_i^2$$

the least squares normal equations for (4) take the form

$$(6) \qquad \begin{cases} A_j l_j + B_j u_j = D_j \\ B_j l_j + C_j u_j = E_j \end{cases}$$

$$(7) \qquad \begin{cases} A_j L_j + B_j v_j = F_j \\ B_j L_j + C_j v_j = G_j \end{cases}$$

where:

$$(8) \qquad \begin{cases} A_j = \sum w_i \\ B_j = \sum w_i t_i \\ C_j = \sum w_i t_i^2 \\ D_j = \sum w_i dx_i \\ E_j = \sum w_i dx_i t_i \\ F_j = \sum w_i dy_i \\ G_j = \sum w_i dy_i t_i \end{cases}$$

$$\sum = \sum_{i \in I(j)}$$

Let

$$M_j = \begin{bmatrix} A_j & B_j \\ B_j & C_j \end{bmatrix}$$

denote the least squares normal matrix of the system (6), (7). Because of the choice of weights w_i, it can be shown that the covariance matrix

$$(9) \qquad R_j = \begin{bmatrix} C_{11j} & C_{12j} \\ C_{12j} & C_{22j} \end{bmatrix} = \begin{bmatrix} \sigma_{1j}^2 & \rho_j \sigma_{1j} \sigma_{uj} \\ \rho_j \sigma_{1j} \sigma_{uj} & \sigma_{uj}^2 \end{bmatrix} \quad (6')$$

$$= \begin{bmatrix} \sigma_{Lj}^2 & \rho_j \sigma_{Lj} \sigma_{vj} \\ \rho_j \sigma_{Lj} \sigma_{vj} & \sigma_{vj}^2 \end{bmatrix} \quad (7')$$

is given by

$$(10) \qquad R_j = M_j^{-1}$$

Defining,

$$(11) \qquad d_j = A_j C_j - B_j$$

it follows that

$$
(12)\quad \begin{cases} \sigma_{lj}^2 = \sigma_{Lj}^2 = C_j/d_j \\ \sigma_{uj}^2 = \sigma_{vj}^2 = A_j/d_j \\ \rho_j\sigma_{lj}\sigma_{uj} = \rho_j\sigma_{Lj}\sigma_{vj} = -B_j/d_j \end{cases}
$$

The equality of the last two matrices in (9) and equations (12) holds only for the assumption of circular errors for the posits. With this assumption, the function W_j decomposes into the sum of two functions which are separately minimized, and simplifies computations considerably. Without the assumption of circular errors for posits, it would be necessary to invert a four by four least squares normal matrix. The solutions of the equations (6), (7) are given by:

$$
(13)\quad \begin{cases} l_j = 1/d_j(C_jD_j-B_jE_j) \\ u_j = 1/d_j(A_jE_j-B_jD_j) \\ L_j = 1/d_j(C_jF_j-B_jG_j) \\ v_j = 1/d_j(A_jG_j-B_jF_j) \end{cases}
$$

which are the solutions that we sought [Ref. 33].

B. MULTI-UNIT RECTIFICATION

Once single unit rectification has been accomplished, the mathematically difficult portion of exercise reconstruction

has been accomplished. As previously discussed, once the rectification process has been completed, translation parameter sets are produced to adjust each track node and these adjustments are performed. The inputs to each parameter set consists of the weighting of each position and the latitude and longitude differentials between the reported positions and its corresponding track node. The combined effect of the total number of positions, total weighting (track quality, time differentials, position type), and the magnitude of the latitude and longitude corrections provide a relative comparison that can be used to determine the precision of each parameter set relative to all the others. This gives an indication of the "fit" of the reconstructed track at each track node. This output precision value can then be used as a relative weighting factor for each single unit track position. By using these weights, in a weighted least squares manner, for separate unit track nodes in corresponding time intervals (essentially the same technique as performed in single unit rectification, described above), Multi-unit (MU) Rectification is accomplished. In the same manner as before, the single units with the "best fits" after Single Unit Rectification (SU) and therefore having the larger weights, have more influence in MU than the "poorer fitted" SU tracks. The relative precision values are not only directly used in the weighting for the MU process, but are part of the printed output from SU for user consumption.

C. PERFORMANCE CHARACTERISTICS

To determine the impact of Navstar GPS on the navigation reconstruction of Naval exercises, it is necessary to discuss navigation errors in general and the performance characteristics of navigation systems which serve as inputs into reconstruction.

1. Navigation Errors

Error in navigation accuracy, as in most systems, reflects "the difference between a specific value and the correct or standard value". Errors fall generally into three classes. Categorized by origin they are: (a) blunders or mistakes; (b) systematic; and (c) "random". Blunders are caused by misreading scales, erroneous computations, etc., and are usually large and easily detected by repeated measurements. Systematic errors obey some fixed law and are generally constant in magnitude and sign within some sequence of measurements ("bias"). Random errors are chance errors, unpredictable in magnitude and sign. Laws of probability provide models for their occurrence, and they are best described and treated by statistical methods. It is often found that system error distributions are Gaussian (normal) or nearly so. They are generally treated as normal random variables.

Although several of the more modern and most interesting navigation problems are three-dimensional, we will limit our discussion of error measurement to the more

conventional two-dimensional spectrum, since exercise reconstruction is generally regarded as a two-dimensional problem (with altitude and/or depth added as necessary). Some of the more commonly used precision indices (statistics) are:

(a) Circular Probable Error (C.P.E. or C.E.P.)--the radius of a circle such that the probability is .5 that an indicated position will lie within the circle. The center of the circle is chosen at the center of mass of the bivariate probability distribution. In an unbiased system the true position lies at the center of the circle; in an unbiased system it does not.

(b) d(rms)--the radius of a circle centered at (M_x, M_y)--the mean X and Y coordinates--in a circular normal distribution containing 0.632 of the total probability.

(c) Circular Standard Error (σ_c)--the radius of a circle centered at (M_x, M_y) in a circular normal distribution containing 0.3935 of the probability. In this circular case $\sigma_x = \sigma_y = \sigma$.

(d) Circular Near-certainty Error--$3.5\sigma_c$. In the circular normal case, there is little real advantage in choosing one of these precision indices over the other, since they are related by constants: C.E.P. = $1.1774\sigma_c$ and d(rms) = $.707\sigma_c$. When the distribution is not circular normal, i.e., $\sigma_x \neq \sigma_y$, but X and Y errors are still normally distributed, the contours of constant probability are ellipses. However, it is notable that probability circles are still very often used even with this knowledge.

2. Navigation Error Sources

Specific types of navigation systems have specific navigation error sources by virtue of the nature of their operation. The following types of system errors will be introduced: hyperbolic, NAVSAT (satellite system), and Navstar GPS. The principal factors of error in low frequency hyperbolic systems such as Loran-C or Omega are:

(a) Incorrect conductivity assumptions

(b) Atmospheric refraction

(c) Failure to correct for velocity as a function of distance

(d) Altitude

(e) Skywave contamination

(f) Atmospheric noise

(g) Slave station synchronization

(h) Station location error

(i) Instrumentation error

(j) Anomalous propagation

These errors caused by skywave contamination, noise, and refraction are largely random in nature and affect the precision or repeatability of the system. The remaining errors appear to be random errors in operating systems, but are, in fact, often systematic errors which are not well determined [Ref. 34].

The principal error sources of the NAVSAT system are:

(a) Instrumentation measurement noise

(b) Signal propagation anomalies

(c) Antenna height estimate error

(d) Error in the satellite orbit prediction

(e) User vehicle velocity error

(f) Position definition errors (round-off, etc.)

The first four errors apply to fixed station position accuracy with (d) being the largest single source of error. All six apply to accuracy when units are underway, with (e) providing the largest source of error for moving units [Ref. 35].

Finally, the principal error sources of Navstar GPS are:

(a) Clock and navigation subsystem stability

(b) Predictability of satellite perturbations

(c) Ephemeris and clock prediction

(d) Ionospheric delay compensation

(e) Tropospheric delay compensation

(f) Receiver noise resolution

(g) Multipath

The errors caused by satellite perturbations, ephemeris and clock prediction, and ionospheric delay are primarily bias errors, while the rest of the errors are random in nature [Ref. 36].

3. Performance Characteristics

In navigation systems performance can usually best be measured in terms of accuracy and reliability. Consider

accuracy first. Taking it as a measure of performance of a navigation system we find various "kinds" of accuracy. These are not comparable, although they are often treated as such in side-by-side comparisons of competitive systems. Common usage of "accuracy" may include any one of the following:

1. The fundamental accuracy limit. For a particular system this is determined by the physical limitations inherent in the method, or by our knowledge of the underlying physical constants. For example, radar is limited by (among other factors) the knowledge of the propagation velocity of electromagnetic waves.
2. Ideal performance today. This is the accuracy attained by existing research and development systems under ideally controlled laboratory conditions. It also comprises predicted system performance based upon present-day component accuracy under laboratory conditions.
3. Ideal performance in the forseeable future. This is the same as (2) except that an extrapolation is made to some future date. The prediction of improved performance is (or should be) based on normal research and development progress; breakthroughs cannot be programmed, and it should not be assumed that they will occur.
4. Operational accuracy. This is the accuracy of the production system operated, calibrated, and maintained

by personnel in the field rather than by the design engineers. Operational accuracy is sometimes estimated by subjecting ideal performance results to some degradation factor.

5. Special operating condition performance. This term refers to accuracy under unfavorable conditions which may further degrade the accuracy from (4). Included in this category are short warm-up times temporary power failures, and high latitudes. In some cases, special conditions may deny use of the system entirely.

Operational accuracy is the usual category of interest to most of us, and is the one in which we usually find data on existing systems.

4. Terminology

Having now chosen between the various kinds of accuracy, we still have the problem that the statistical terminology for describing accuracy is not standardized. First of all, the technical distinction between accuracy and precision, as previously discussed, is mixed in many presentations. The common uses of accuracy given above ordinarily combine the assessment of accuracy and precision into a single accuracy figure. For navigation systems, the accuracy (that is, the closeness of average position to the true position) and the precision (a small dispersion) can be treated together as the error characteristic. Blunders and equipment failures can be considered together as the

reliability characteristic. All of these factors are considered to be performance characteristics, which are a subset of the operational characteristics of a system [Ref. 37].

D. COMPARISON OF OPERATIONAL CHARACTERISTICS

To determine the impact of Navstar GPS on the reconstruction of Naval exercises, it is advantageous to examine some of the more common navigation systems used by the Navy and their operational characteristics to determine if Navstar would improve the performance of the reconstruction process. The more common navigation systems presently used by the Navy that will be selected for comparison with Navstar GPS are: Loran-C, Omega, and NAVSAT (NNSS). Some of the characteristics that will be examined will be: coverage, signal reliability, data content, accuracy, application versatility, fix rate, and relative cost of user equipment.

To illustrate the full potential of Navstar GPS, the following paragraphs will compare and contrast it with other selected navigation systems. They will emphasize limitations that Navstar does not have. The intent, in this case, is to highlight Navstar and not to downgrade the other systems.

Comparing Navstar GPS with Loran-C, Loran-C can, in very good signal areas, produce a repeatability and resolution as good as 15 to 30 meters (nominally, in all areas 50 to 300 ft), which is better than some of the low cost GPS sets. The principal disadvantages of Loran-C as compared to Navstar are:

	LORAN-C	OMEGA	NAVSAT	NAVSTAR
DESCRIPTION	Pulsed Hyperbolic	CW Hyperbolic	Satellite Doppler	Satellite UHF Passive Range
COVERAGE	1200 nm N. America W. Pac, W. Lant Mediterranean	90% Global	Global	Global
SIGNAL RELIABILITY	Fair (100 KHz)	Fair (10-14 KHz)	High (150, 400 MHz)	High (1230, 1575 MHz)
DATA CONTENT	Absolute 2D Posit	Absolute 2D Posit	Absolute 2D Posit	Absolute 3D Posit, 3D Velocity Time
ACCURACY (95% PROB)	1500 ft, 50-300 ft (reliabil)	2-4 nm	500 m	20-38 m (horiz) 25-47 m (vertical)
APPLICATION VERSATILITY	Air, Surf, Med Dist, Weps Deliv	Air, Surf, Underwater, Long Dist.	Surface, Intermit. Posit	Air, Surf, Space, Long Dist., Term Weps Deliv
FIX RATE	25/sec	1/10 sec	1/30 min-1/110 min	Continuous
UE COST	Moderate	Low	Moderate	Moderate to High (Var. Perf UE Develop)

Source: [Refs. 38,39]

Figure 5.1. Comparison of Operational Characteristics

Coverage--A user can get good navigation performance in areas where the signals exist, but only a relatively small area of the world is covered by these signals.

Positional Reliability--Loran receivers must identify and track the third cycle of each pulse. Sometimes this cycle selection can fail without warning to the navigator and produce a typical navigation error of 2 nm.

Grid distortion--Navigation errors of a half mile or more can occur because of grid distortion. There are two phenomena that contribute to this distortion, requiring two corrections. One is the secondary phase correction, and is a known function for an all seawater path. The other is the "additional secondary factor" (ASF) which includes the anomalies of land masses, etc. These corrections are available in tabulated form. Navigation charts can normally be corrected for this distortion, but automatic latitude/longitude sets usually do not provide this compensation.

Interfering signals--Loran-C receivers must be equipped with adjustable notch filters in order to cancel signals which interfere with proper operation of the set. In widespread application, the navigator must be trained to adjust these filters to get optimal performance.

Weather problems--Loran-C suffers from weather related problems such as static caused by light rain or mist.

Therefore, although Loran-C does have comparable repeatable accuracy, its absolute accuracy and coverage are its primary limitations when compared to GPS.

Comparing Navstar GPS to Omega, Omega provides near world-wide navigation coverage with only eight transmitting stations, while Navstar needs at least twenty-three stations (18 satellite, 4 ground monitor stations, and 1 master control station). Omega limitations as compared to Navstar are:

Repeatability--At a fixed location, the indicated position wanders with a non-Normal distribution. A half mile repeatability error occurs with about fifty percent probability, with a peak of two or three nautical miles with about ten percent probability.

Positional Reliability--Due to a number of different problems, including lane count slips, polar cap anomalies, sudden ionospheric disturbances, long path reception, etc., Omega position accuracies can suddenly increase dramatically (errors of ten, thirty, or one hundred miles have been noted). Some of these problems can be anticipated, but others can not.

Skywave corrections--Successful Omega navigation requires the application of skywave corrections. However, local as well as large scale distortions can exist.

Weather limitations--Precipitation static affects Omega as it does Loran-C.

Coverage limitations--Omega was intended to have world-wide coverage, but due to station reception difficulty in parts of the world, it is not capable of providing 24-hour world-wide coverage.

Again, as in the case of Loran-C, Omega is not as accurate (either absolutely or repeatably) as Navstar GPS nor does it provide as good coverage as this new system.

Comparing Navstar GPS and the Navy Navigation Satellite System (NAVSAT), the major advantage of NAVSAT is that it consists of only five satellites orbiting about 600 miles high, while the GPS system will consist of eighteen satellites at about 10,900 miles above the earth. NAVSAT provides accurate position fixes on a world-wide basis, as will GPS, but the absolute position accuracy of NAVSAT is on the order of 500m (95% prob.) compared to 20 to 38m (95% prob.) for GPS. The areas where NAVSAT is less competitive are:

Update Interval--The NAVSAT system can provide a single position fix each time one of the satellites is in electronic "view" of the user. The interval between fixes averages about 90 minutes, but can

be several hours in positions of low latitude. GPS fixes are continuously available.

Repeatability--Although the accuracy of a NAVSAT fix is somewhat competitive with that of Navstar, this accuracy is degraded by unknown ship's velocity, therefore ship navigation accuracy is rapidly degraded as DR information accuracy varies degradably (0.25 nm error/knot of velocity inaccuracy) [Ref. 40].

Therefore, Navstar GPS is a "better performer" than the other selected (comparable) systems. It is more accurate (absolute accuracy) than NAVSAT (20 to 38m-horizontal error vs. 500m at 95% probability level) (Navstar had a 22.0m 3D error at 90% probability for all tests in Phase I of its Test and Evaluation or Acquisition cycle), its closest competitor. Loran-C can compete with some of the lower cost GPS UE in terms of repeatability (at 15 to 30m), but only in good signal areas. In terms of coverage, NAVSAT can compete world-wide, but not continuously as GPS can. Omega can provide only about 90% coverage of the world. NAVSAT and Navstar are truly all-weather systems, whereas Loran-C and Omega are not. However, again NAVSAT provides fixes in all weather, nominally, every 90 minutes, whereas Navstar fixes are continuous. These operational (performance) characteristics are the basis for the claim that Naval exercise reconstruction will improve with Navstar GPS position fixing

input. Coverage will truly be world-wide. Accuracy will improve on the order of greater than a factor of ten over the closest competitor. GPS will not be weather degraded. GPS fixes will be continuous (in all but submerged units, but even their track endpoints will be more accurate and precise).

This performance improvement will not be without cost. The best performance equipments will also be the most costly of any of the receivers. Current cost projections put the 5-channel units in the $43,000 price range and the 2-channel sets at about $26,000 depending, of course, on the number that will be bought [Ref. 41]. This is about a tenfold increase in price over the average price of some of the other types of receivers. However, the primary reason that most Navstar receivers will go aboard most military units, will be to improve navigation accuracy and weapons delivery capabilities, so in that regard, Naval exercise reconstruction capabilities will improve without much additional cost. Some costs will be incurred by the purchasing of temporary (portable) units that will be required by NTSA and other costs will be required to modify some existing NTSA equipments. However, the increased benefits reaped from reconstruction should outstrip these costs, if viewed from the perspective of this paragraph.

VI. CONCLUSIONS AND RECOMMENDATIONS

Navstar GPS does have an application in Naval exercise reconstruction. Navstar by virtue of its accuracy, coverage, fix rate, and flexibility can provide a significant improvement in navigation track reconstruction of Naval exercises when coupled with a system such as the Mini-Reconstruction System. GPS is truly a world-wide, highly accurate, all-weather, continuous position fixing navigation system. Navstar data input into the MRS can not only provide improved reconstruction capability, but can provide this capability in real time. This combining of the two systems has the additional advantage of being able to use existing operational equipment or prototype equipment with only very minor modifications to combine these systems into a viable reconstruction process. This should insure that no long lead time or high research and development costs are incurred in this combined application. However, MRS is not an infallible system. It has limitations in the size of the exercises that it can reconstruct and in the lack of Electronic Warfare (EW) reconstruction capability.

GPS itself will cost more than other similar type navigation systems, presently in use, but those costs will be returned in the form of better navigation accuracy and precision, resulting in fewer collisions, groundings, etc., and

better weapons delivery capability. Therefore, improved exercise reconstruction could be considered to be a bonus benefit that was not designed as a primary application for Navstar. When viewed in this manner, this improved reconstruction capability could be considered to be relatively inexpensive.

An attempt has been made to use GPS as an accurate "ground truth" track for reconstruction of a Naval exercise (Rimpack '80), based on the Manpack UE. However, this is not the methodology that was described in this thesis. This application is based on the traditional Naval navigation principle that requires the use of all available navigation system inputs to determine a position (or in this case, a track). This method attempts to use all available navigation inputs, weights them according to their relative accuracies, and develops a composite least squares "fitted" track.

It is recommended that NTSA study the feasibility of development of exercise data collection equipments incorporating Navstar GPS inputs, similar to those described in this paper. Additional studies could be conducted to determine the cost effectiveness of this or other similar type reconstruction system applications, as this was not a primary focus of this paper. Other recommendations are that alternative, competitive reconstruction systems be compared to determine the most efficient systems for use by the Navy once GPS input is readily available. This paper looked at

only one such system with no attempt to endorse it as the best alternative available. Finally, it is recommended that studies be conducted or action taken to produce a MRS type system to reconstruct full scale Naval exercises in real time for realistic battle evaluations by both local commanders and exercise umpires.

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